3 STATISTICAL INTERPRETATIONS OF MINIMUM DETECTABLE CONCENTRATIONS

Detection limits for field survey instrumentation are an important criterion in the selection of appropriate instrumentation and measurement procedures. For the most part, detection limits need to be determined in order to evaluate whether a particular instrument and measurement procedure is capable of detecting residual activity at the regulatory release criteria (DCGLs). One may demonstrate compliance with decommissioning criteria by performing surface activity measurements and directly comparing the results to the surface activity DCGLs. However, before any measurements are performed, the survey instrument and measurement procedures to be used must be shown to possess sufficient detection capabilities relative to the surface activity DCGLs; i.e., the detection limit of the survey instrument must be less than the appropriate surface activity DCGL.

The measurement of residual radioactivity during surveys in support of decommissioning often involves measurement of residual radioactivity at near-background levels. Thus, the minimum amount of radioactivity that may be detected by a given survey instrument and measurement procedure must be determined. In general, the minimum detectable concentration (MDC) is the minimum activity concentration on a surface or within a material volume, that an instrument is expected to detect (e.g., activity expected to be detected with 95% confidence). It is important to note, however, that this activity concentration, or the MDC, is determined *a priori*, that is, before survey measurements are conducted.

As generally defined, the detection limit, which may be a count or count rate, is independent of field conditions such as scabbled, wet, or dusty surfaces. That is, the detection limit is based on the number of counts and does not necessarily equate to measured activity under field conditions. These field conditions do, however, affect the instrument's "detection sensitivity" or MDC. Therefore, the terms MDC and detection limit should not be used interchangeably.

For this study, the MDC corresponds to the smallest activity concentration measurement that is practically achievable with a given instrument and type of measurement procedure. That is, the MDC depends not only on the particular instrument characteristics (instrument efficiency, background, integration time, etc.), but also on the factors involved in the survey measurement process (EPA 1980), which include surface type, source-to-detector geometry, and source efficiency (backscatter and self-absorption).

3.1 MDC Fundamental Concepts

The scope of this report precludes a rigorous derivation of MDC concepts, yet sufficient theory is presented to acquaint the user of this manual with the fundamental concepts. The detection limits discussed in this report are based on counting statistics alone and do not include other sources of error (systematic uncertainties in the measurement process are addressed in NUREG/CR-4007 and ANSI N13.30). Although the following statistical formulation assumes a normal distribution of net counts, between sample and blank, it should be recognized that this may not be the case for low blank total counts. However, in consideration of the advantage of having a single, simple MDC expression, and the fact that deviations from the normality assumption do not affect the MDC expression contained herein as severely as had been expected (Brodsky 1992), it was decided that the normality assumption was proper for purposes of this report. That is, the MDC concepts discussed below should be considered as providing information on the general detection capability of the measurement system, and not as absolute levels of activity that can or cannot be detected (NCRP 58).

The MDC concepts discussed in this document derive from statistical hypothesis testing, in which a decision is made on the presence of activity. Specifically, a choice is made between the null hypothesis (H_0) and the alternative hypothesis (H_a). The null hypothesis is generally stated as "no net activity is present in the sample" (i.e., observed counts are not greater than background), while the alternative hypothesis states that the observed counts are greater than background, and thus, that net activity is present. These statements are written:

> H_0: No net activity is present in the sample, and
> H_a: Net activity is present in the sample.

It should be noted that the term "sample" has a general meaning in this context, it may apply to direct measurements of surface activity, laboratory analyses of samples, etc.

A first step in the understanding of the MDC concepts is to consider an appropriate blank (background) distribution for the medium to be evaluated. Currie (1968) defines the blank as the signal resulting from a sample which is identical, in principle, to the sample of interest, except that the residual activity is absent. This determination must be made under the same geometry and counting conditions as used for the sample (Brodsky & Gallaghar 1991). In the context of this report, an example of this medium may be an unaffected concrete surface that is considered representative of the surfaces to be measured in the remediated area. It should be noted that the terms blank and background are used interchangeably in this report.

In this statistical framework, one must consider the distribution of counts obtained from measurements of the blank, which may be characterized by a population mean (μ_B) and standard deviation (σ_B). Now consider the measurement of a sample that is known to be free of residual activity. This zero-activity (background) sample has a mean count (C_B) and standard deviation (s_B). The net count (and, subsequently, residual activity) may be determined by subtracting the blank counts from the sample counts. This results in a zero-mean count frequency distribution that is approximately normally distributed (Figure 3.1). The standard deviation of this distribution, σ_0, is obtained by propagating the individual errors (standard deviations) associated with both the blank (σ_B) and the zero-activity samples (s_B). That is,

$$\sigma_0 = \sqrt{\sigma_B^{\,2} + s_B^{\,2}} \tag{3-1}$$

A critical level may then be determined from this distribution and used as a decision tool to decide when activity is present. The critical level, L_C, is that net count in a zero-mean count distribution having a probability, denoted by α, of being exceeded (Figure 3.1). It is a common practice to set α equal to 0.05 and to accept a 5% probability of incorrectly concluding that activity is present when it is not. That is, if the observed net count is less than the critical level, the surveyor correctly concludes that no net activity is present. When the net count exceeds L_C, the null hypothesis is rejected in favor of its alternative, and the surveyor falsely concludes that net activity is present in the blank sample. It should also be noted that the critical level, L_C, is equivalent to a given probability (e.g., 5%) of committing a Type I error (false positive detection). The expression for L_C is generally given as:

$$L_C = k_\alpha \, \sigma_0 \tag{3-2}$$

where k_α is the value of the standard normal deviate corresponding to a one-tailed probability level of $1-\alpha$. As stated previously, the usual choice for α is 0.05, and the corresponding value for k_α is 1.645. For an appropriate blank counted under the same conditions as the sample, the assumption may be made that the standard deviations of the blank and zero-activity sample are equal (i.e., σ_B equals s_B). Thus, the critical level may be expressed as:

$$L_C = 1.645 \sqrt{2 \, s_B^{\,2}} = 2.33 \, s_B \tag{3-3}$$

The L_C value determined above is in terms of net counts, and as such, the L_C value should be added to the background count if comparisons are to be made to the directly observable instrument gross count.

The detection limit, L_D, is defined to be the number of mean net counts obtained from samples for which the observed net counts are almost always certain to exceed the critical level (Figure 3.2). It is important to recognize that L_D is the mean of a net count distribution. The detection limit is positioned far enough above zero so that there is a probability, denoted by β, that the L_D will result in a signal less than L_C. It is common practice to set β equal to 0.05 and to accept a 5% probability of incorrectly concluding that no activity is present, when it is indeed present (Type II error). That is, the surveyor has already agreed to conclude that no net activity is present for an observed net count that is less than the critical level, however, an amount of residual activity that would yield a mean net count of L_D is expected to produce a net count less than the critical level 5 % of the time. This is equivalent to missing residual activity when it was present.

The expression for L_D is generally given as:

$$L_D = L_C + k_\beta \, \sigma_D \tag{3-4}$$

where k_β is the value of the standard normal deviate corresponding to a one-tailed probability level of $1-\beta$ for detecting the presence of net activity, and σ_D is the standard deviation of the net sample count (C_S) when C_S equals L_D. For clarification, consider the measurement of a sample that provides a gross count given by C_{S+B}., at the detection level. The net sample count, C_S , is calculated by subtracting the mean blank count (μ_B) from the gross count. The detection limit may be written as follows, recognizing that C_S equals L_D :

$$L_D = C_S + (C_B - \mu_B) \tag{3-5}$$

The standard deviation of the net sample, σ_D , is obtained by propagating the error in the gross count and from the background when the two are subtracted to obtain L_D. As previously noted, the standard deviation of this distribution, σ_0, is obtained by propagating the uncertainties associated with both the blank (C_B) and the zero-activity samples (μ_B), therefore,

$$\sigma_D = \sqrt{(C_S + \sigma_o^2)} = \sqrt{(L_D + \sigma_o^2)} \tag{3-6}$$

This expression for σ_D may be substituted into Equation 3-4 and the equation solved for L_D.

As stated previously, the usual choice for β is 0.05, and the corresponding value for k_β is 1.645. If the assumption is made that σ_D is approximately equal to the standard deviation of the background, then for the case of paired observations of the background and sample σ_o^2 equals $2s_B^2$. Following considerable algebraic manipulation, the detection limit may be expressed as:

$$L_D = 2.71 + 4.65\ s_B \tag{3-7}$$

The assumption that the standard deviation of the count (σ_D) is approximately equal to that of the background greatly simplifies the expression for L_D, and is usually valid for total counts greater than 70 for each sample and blank count (Brodsky 1992). Brodsky has also examined this expression and determined that in the limit of very low background counts, s_B would be zero and the constant 2.71 should be 3, based on a Poisson count distribution (Brodsky & Gallaghar 1991). Thus, the expression for the detection limit becomes:

$$L_D = 3 + 4.65\ s_B \tag{3-8}$$

The detection limit calculated above may be stated as the net count having a 95% probability of being detected when a sample contains activity at L_D, and with a maximum 5% probability of falsely interpreting sample activity as activity due to background (false negative or Type II error).

The MDC of a sample follows directly from the detection limit concepts. It is a level of radioactivity, either on a surface or within a volume of material, that is practically achievable by an overall measurement process (EPA 1980). The expression for MDC may be given as:

$$MDC = \frac{(3 + 4.65\ s_B)}{KT} \tag{3-9}$$

where K is a proportionality constant that relates the detector response to the activity level in a sample for a given set of measurement conditions and T is the counting time. This factor typically encompasses the detector efficiency, self-absorption factors, and probe area corrections.

This expression of the MDC equation was derived assuming equivalent (paired) observations of the sample and blank (i.e., equal counting intervals for the sample and background), in contrast to the MDC expression that results when taking credit for repetitive observations of the blank (well-known blank). There is some debate concerning the appropriateness of taking credit for repetitive observations of the blank, considering the uncertainties associated with using a well-known blank for many samples when there can be instrument instabilities or changes in the measurement process that may be undetected by the surveyor (Brodsky & Gallaghar 1991). Therefore, it is desirable to obtain repetitive measurements of background, simply to provide a better estimate of the background value that must be subtracted from each gross count in the determination of surface activity. Thus, the background is typically well known for purposes other than reducing the corresponding MDC, such as to improve the accuracy of the background value. The expression for MDC that will be used throughout this report is given as:

$$MDC = \frac{3 + 4.65\sqrt{C_B}}{KT} \tag{3-10}$$

where C_B is the background count in time, T, for paired observations of the sample and blank. For example, if ten 1-minute repetitive observations of background were performed, C_B would be equal to the average of the ten observations and T is equal to 1 minute. The quantities encompassed by the proportionality constant, K, such as the detection efficiency and probe geometry, should also be average, "well-known" values for the instrument. For making assessments of MDC for surface activity measurements, the MDC is given in units of disintegrations per minute per 100 square centimeters (dpm/100 cm^2).

For cases in which the background and sample are counted for different time intervals, the MDC becomes (Strom & Stansbury 1992)

$$MDC = \frac{3 + 3.29\sqrt{R_B\ T_{S+B}\ (1 + \frac{T_{S+B}}{T_B})}}{KT_{S+B}} \tag{3-11}$$

where R_B is the background counting rate, and T_{S+B} and T_B are the sample and background counting times, respectively.

One difficulty with the MDC expression in Equation 3-10 is that all uncertainty is attributed to Poisson counting errors, which can result in an overestimate of the detection capabilities of a measurement process. The proportionality constant, K, embodies measurement parameters that have associated uncertainties that may be significant as compared to the Poisson counting errors. A conservative solution to this problem has been to replace the parameter values (specifically the mean parameter values) that determine K with lower bound values that represent a 95% probability that the parameter values are higher than that bound (NUREG/CR-4007; ANSI N13.30). In this case, the MDC equation becomes

$$MDC = \frac{3 + 4.65\sqrt{C_B}}{K_{0.05}T} \tag{3-12}$$

where $K_{0.05}$ is the lower bound value that represents a 95% probability that values of K are higher than that bound (ANSI N13.30). For example, if the detector efficiency in a specified measurement process was experimentally determined to be 0.20 ± 0.08 (2σ error), the value of the detector efficiency that would be used in Equation 3-10 is 0.12. This would have the effect of increasing the MDC by a factor of 1.7 (using 0.12 instead of 0.20). Therefore, it is important to have an understanding of the magnitude of the uncertainty associated with each of the parameters used in the MDC determination. In this context, errors associated with each measurement parameter were propagated in the MDC determination. The magnitude of the uncertainty in the MDC may then be used as a decision tool, allowing for determination of the need to implement some methodology for adjusting the MDC for uncertainties in *K*.

3.2 Review of MDC Expressions

A significant aspect of this study involved the review of the relevant literature on statistical interpretations of MDC. One approach, suited for this application of the MDC concept, was selected and used throughout the entire study, for consistency. However, other statistical approaches were considered in a sensitivity study. That is, the same set of measurement results were used to calculate the MDC, using several statistical treatments of the data. The tabulated results provided the range of MDC values, calculated using the various approaches.

The data used to perform the MDC sensitivity analysis were obtained by performing static measurements under ideal laboratory conditions with a gas proportional detector, operated in the beta-only mode, on a SrY-90 source (the expressions for scanning sensitivity were not evaluated in this part). For purposes of comparison, both the background and sample counting times were one minute long, i.e., paired observations. Ten repetitive measurements of background were obtained and the mean and standard deviation were calculated to be 354 and 18 counts, respectively. The total efficiency of the detector was determined to be 0.34 count per disintegration and probe area correction for 126-cm^2 detector was made.

Several expressions of MDC (or the various terms used to convey detection limit) were reviewed in the literature. The measurement results determined above were used to determine the values for the various expressions of MDC. The average background from the repetitive observations was used in the MDC equations that required a background value, while the standard deviation of the background distribution was used for others. Table 3.1 illustrates the variations in MDC that may be calculated from the same set of measurement results. The MDC values ranged from 146 to 211 dpm/100 cm^2, for the gas proportional detectors calibrated to SrY-90.

This limited MDC sensitivity study demonstrates that the MDC expressions widely referenced in the literature produce very consistent MDC results. The smallest value of MDC results from the expression that allows credit to be taken for the “well-known” blank (Currie 1968). There would likely be no difference in the conclusion that would be reached concerning the demonstration that the instrumentation possesses sufficient detection capabilities relative to the surface activity DCGLs.

Table 3.1 MDC Results for Data Obtained From Gas Proportional Detector Using Various MDC Expressions

MDC Expression[a,b]	MDC Result[c] (dpm/100 cm^2)	Reference
$2.71 + 4.65\sqrt{B}$	210	NCRP 58 EPA 1980
$2.71 + 4.65\,\sigma_B$	204	Currie 1968
$2.71 + 3.29\,\sigma_B$	146	Currie 1968
$3 + 4.65\sqrt{B}$	211	Brodsky & Gallaghar 1991
$\dfrac{3 + 3.29\sqrt{R_b\, t_g\, (1 + \frac{t_g}{t_b})}^{\,d}}{(Efficiency)(t_g)}$	211	Strom & Stansbury 1992

[a]The data used in each MDC expression were obtained from a 43-68 gas proportional detector and SrY-90 source. Average background counts (B) of 354 in 1 minute, standard deviation of 18, probe area correction for 126-cm^2 detector, and detector efficiency of 0.34 count per disintegration were obtained.

[b]Each MDC expression is written using symbols that may be different from the ones that were presented in their respective references. However, the meaning of each has been preserved.

[c]Each MDC result was presented in terms of dpm/100 cm^2 to facilitate comparison of the different MDC expressions. This involved correcting the MDC expression for probe area and detector efficiency.

[d]The terms R_b, t_g, and t_b refer to the background counting rate, gross count time, and background counting time, respectively. Using t_g equal to t_b (1 minute), resulted in the same expression as that of Brodsky and Gallaghar (1991).

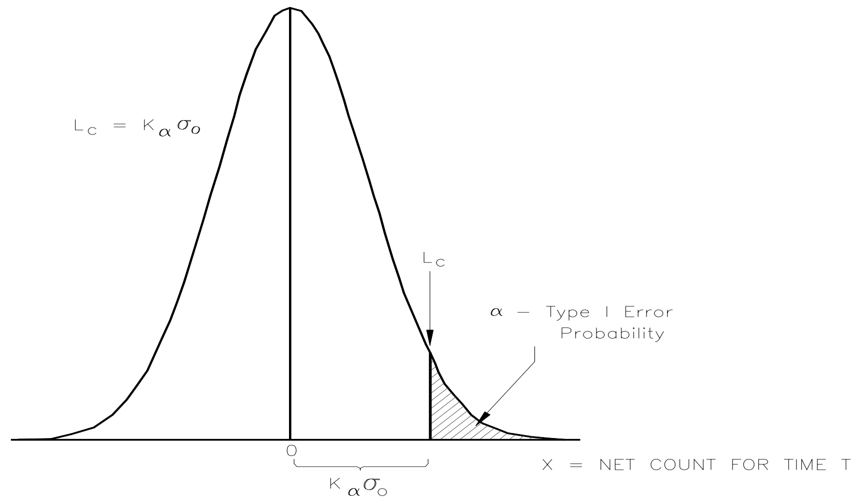

Figure 3.1: Critical Level, L_C

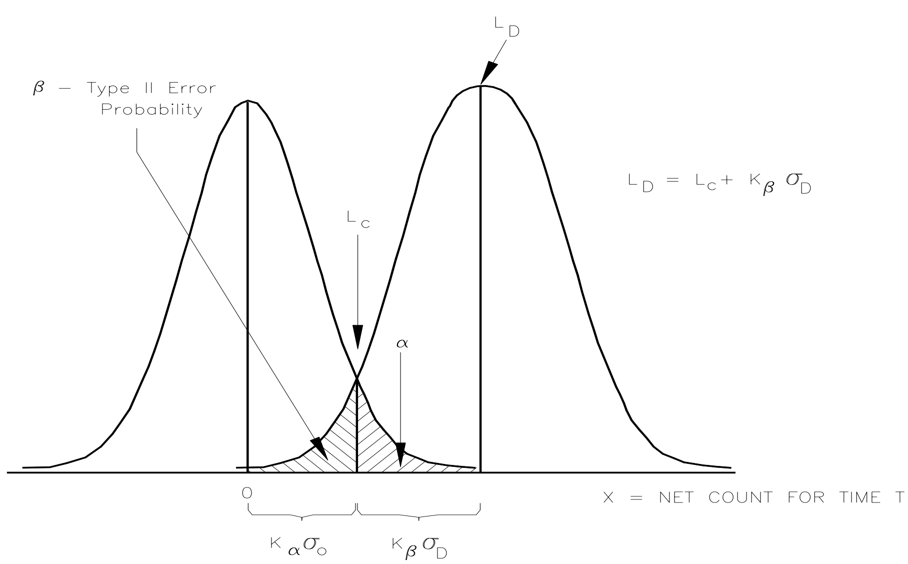

Figure 3.2: Detection Limit, L_D